1. *PI*:

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2. *Title*:

Development and Evaluation of Boundary Layer Cloudiness Parameterizations Using ARM Observations

3 *Scientific Goals*:

This project is designed to address key issues regarding the treatment of boundary clouds in climate models. Since boundary layer clouds are intimately connected to the boundary layer turbulence and surface fluxes, these processes need to be considered (parameterized) to develop realistic parameterizations. Specific goals include: 1) use observations from the Southern Great Plains (SGP) ARM site to develop statistical descriptions of cloud and boundary layer structures and to develop a physical understanding of the processes associated with the formation, maintenance, and dissipation of continental boundary layer clouds, 2) use observations from SGP site with observations from the UM 94 GHz radar obtained during the Spring 2000 Cloud IOP to develop Large Eddy Observations (LEO) of continental stratus clouds for the evaluation of boundary layer cloud parameterizations and Large Eddy Simulations (LES), and 3) use observations from the Nauru Island ARM site to initiate a study of fair-weather cumulus clouds that focuses on the evaluation of parameterizations and the use of LEO for the evaluation of LES and Cloud Resolving Models (CRMs).

4. *Accomplishments*:

- Further developed climatology of boundary layer structure and macroscopic cloud properties from ARM SGP data for 1995-1999 with ongoing updating of the data base.

- Demonstrated the validity of using Doppler cloud radar observations to study turbulence and updraft/downdraft structures in boundary layer clouds.

- Developed a scheme for predicting boundary cloud formation under stable conditions with high wind shear.

- Participated in the ARM Spring 2000 Cloud IOP to collect GHz reflectivity and Doppler observations with the UM 94 GHz radar.

5. *Progress and Accomplishments*:

Work on this grant continues to focus on the analysis of data from continental stratus clouds observed at the ARM Southern Great Plains site (SGP) and the development and testing of remote sensing techniques applicable to the ARM CART measurements. Cloud and boundary layer products produced as part of these studies are being made available to other ARM investigators.

Major efforts under this grant include: 1) the development of stratus cloud climatologies, 2) the evaluation of processes involved in the formation of boundary layer clouds, and 3) the description and parameterization of the turbulence structure in boundary layer clouds using mm-wavelength radar observations.

a. Stratus Cloud Climatology Statistics

Observations from the Belfort ceilometer and the micro-pulse lidar were used to identify periods when boundary layer clouds are present over the SGP site. During the period from 1996-1999 approximately 4700 hours of boundary layer clouds were present over the SGP CART site. Hourly statistics for this period provide cloud base height, lifting condensation level, surface meteorology, liquid water path, and surface fluxes of heat and moisture. Cloud-top height and cloud thickness have only been compiled for the late fall and winter months in 1997, since the detection of non-meteorological targets (NMT) by the MMCR complicate the retrieval of cloud top. All the cloud cases from 1997 were subjectively classified into synoptic classifications. These results indicate the seasonal variability and the wide-range of synoptic conditions, particularly in the wind profiles, associated with stratus clouds observed at the SGP site. Preliminary results from these statistical studies are described in papers presented at the 1999 ARM Science Team Meetings and a full manuscript describing these results has been drafted for submission to the *J. of Climate*.

We are also actively evaluating techniques to objectively classify the stratus into distinct weather regimes through a principal component analysis (PCA) approach. Through preliminary work on the 1996-1999 dataset, it is evident that the objective analysis identifies distinct differences in cloud macroscopic and boundary layer properties such as the diurnal distribution of cloud base height and mean profiles of potential temperature, mixing ratio, and wind speed and direction. We plan on improving this technique by removing seasonal effects and by identifying additional parameters by which to objectively group the data such as boundary layer stability.

A web page at the University of Miami designed specifically for the ARM project (http://orca.rsmas.miami.edu/arm/index.html) provides images for 1996-2000 products. The archive gives the research community access to more closely screened data sets (both processed data files and images) of individual stratus cloud cases. The archive also provides a subset of data for investigators who want to focus on stratus clouds for both process and modeling studies without having to search through all of the ARM data to identify these cases. A case study for the latest model intercomparison performed by the GCSS-WG1 [GEWEX (Global Water and Energy Experiment)] Cloud Systems Working Group One] was for a continental boundary layer cloud selected from this ARM data set.

b. Process Studies

Studies are in progress to better understand the processes responsible for the formation of stratus clouds and the fractional amount of boundary layer clouds. These studies focus on formation of nocturnal stratus under stable conditions and the daytime development of boundary layer clouds under unstable conditions. For the nocturnal stratus the importance of wind shear for cloud formation is considered. For the daytime stratus studies, the focus is on the diurnal cycle and the coupling between the clouds and the LCL. These studies use case studies to demonstrate key processes that are then used to develop more extensive strategies for developing statistical analyses using the full ARM data bases. Although these studies focus on cloudy conditions, we also make comparisons with surface conditions and boundary layer structure observed under clear conditions. The clear cases provide a baseline for interpreting the cloud results. Furthermore, it is important that cloud parameterizations properly recognize conditions when there are no boundary layer clouds. The observations from the boundary, intermediate, and extended facilities surrounding the central SGP are used to define mesoscale variability in the study area. To further consider mesoscale effects and to study land-atmosphere interactions, the Regional Atmospheric Modeling System (RAMS) has been used to predict boundary layer cloud development using ARM data to initialize the model and evaluate the simulated cloud formation. Case studies made during clear and cloudy nighttime conditions have been used to examine the role of wind shear on cloud formation. Wind shear and the surface heat fluxes from the ARM data were used to calculate a critical mixing depth (h-critical) that can be compared with the LCL to determine if the formation of clouds is possible. This case study along with model simulations and additional statistical analyses of the ARM data indicate the that wind shear can be an important factor in the formation of stratocumulus clouds for a range of surface moisture and heat flux conditions. This work is part of Ping Zhu's thesis research. Presentations of this work were made at 1999 ARM Science Team Meeting. A manuscript that describes this work has been reviewed for inclusion in the *Journal of Atmospheric Sciences* and a revised version of this paper has been resubmitted.

The utility of the ARM data for further study of daytime cases associated with boundary layer clouds has also been clearly demonstrated. A full characterization of the cloud and boundary layer evolution for the diurnal cases are being made for a wide range of cases. The validity of simple mixed layer theory for defining the evolution of the mean LCL and the boundary layer depth is being evaluated and used to evaluate cloud onset. This work is also part of Ping Zhu's thesis research.

c. Large-Eddy Observations in Support of Large Eddy Simulations (LEO for LES)

Techniques were developed for examining the turbulence structure of stratus clouds and for testing simple mass flux representations of the vertical velocity fields in the clouds. As part of this, the turbulent-scale vertical velocity structure in a continental stratocumulus cloud was studied using a 3-mm wavelength Doppler radar operating in a vertically pointing mode. The radar observations provided 30 m resolution in the vertical with 2-second averages of 10,000 samples. A detailed analysis of the vertical-velocity perturbations in this cloud was obtained as the cloud evolved from a well-mixed case to a more decoupled case during the 8-hour study. This study illustrated the use of cloud radar vertical velocities for comparing directly observed updraft fractional coverage and mass flux with those obtained from the bulk statistics. These comparisons are remarkably consistent with similar comparisons made using LES models. Decomposition of the variances have been used to examine the validity of mass flux representations that are used in some boundary layer parameterizations. This study further illustrates the utility of mm-wavelength radars for studying turbulence in boundary layer clouds and particularly in defining the vertical structure of coherent eddies (LEO) that can be compared with LES and CRMs. A paper that describes these in press for publication in *the Journal of Atmospheric Sciences*.

Additional observations from non-precipitating stratus clouds were obtained with the UM 94 GHz cloud radar during the Spring 2000 Cloud IOP. These will used to examine the potential of using the MMCR to provide LEO. Observations have also been made in fair-weather cumuli sampled by the UM Radar during operation in South Florida. These detailed cloud radar observations (paper submitted to *Journal of Atmospheric Sciences*) will be used to evaluate the potential of using the MMCR measurements from Nauru to obtain statistics on the dynamics of fair-weather cumuli observed at that site.

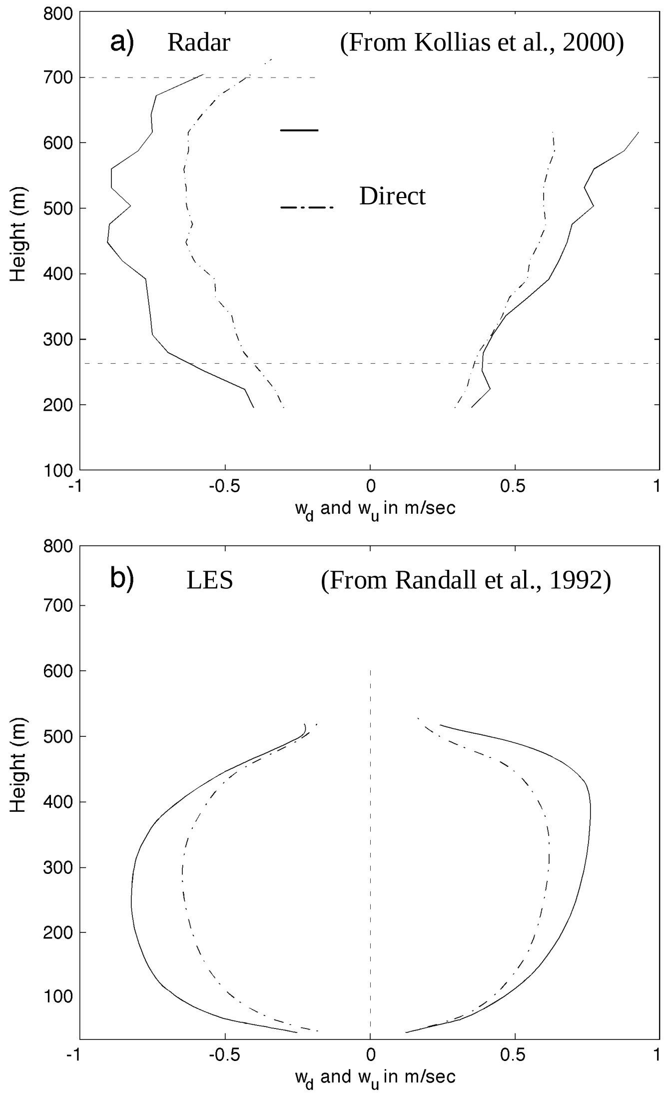
6. *Highlight Figure* – See bottom of document

7. Refereed Publications:

Kollias, P., B.A., Albrecht, R. Lhermitte, and A. Savtchenko, 2000: Radar observations of updrafts, downdrafts, and turbulence from fair weather cumuli. *J. Atmos. Sci*. (submitted)

Kollias, P., and B. Albrecht, 2000: The turbulence structure in a continental stratocumulus cloud from millimeter-wavelength radar observations. *J. Atmos. Sci*. (In press).

Zhu, P., B. Albrecht, and J. Gottschlack, 2000: Formation and development of nocturnal boundary Layer clouds over the Southern Great Plains. *J. Atmos. Sci*. (submitted).



Large Eddy Observations in a Continental Stratus Cloud Using a Cloud Radar

Vertical velocity observations from a continental stratus cloud obtained with a 94 GHz Doppler cloud radar in vertically pointing mode were used (Panel a) to obtain average updraft w_u and downdraft w_d velocities from direct observations (dashed line) for comparison with draft characteristics calculated from the vertical velocity variance and skewness (sold line) using formulation from, the Randall et al. (JAS, 1992, p. 1903-1923) bulk boundary layer model. These observations are for samples obtained every 2 seconds during an hour-long period. Bottom panel is Figure 3a from Randall et al. (1992) and shows the same comparison of directly sampled and statistically calculated updraft and downdraft characteristics from LES stratocumulus results. The similarity between the LEO and LES results are very encouraging and support the use of high resolution radar observations for evaluating fundamental aspects of boundary layer parameterizations.